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Guided-wave-produced-plasmas

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The abstract of a topical lecture on diffusion-controlled gas discharges sustained in the field of travelling waves is presented in this contribution. Based on discharge models within the fluid plasma theory, the maintenance of discharges without and in external magnetic field is discussed. The mechanisms of the discharge self-consistency and of the electron heating are shown. The final results from the models are for the self-consistent axial structure of the discharges.

1. General comments on guided-wave-produced plasmas

The guided-wave-sustained discharges (GWSDs) are comparatively new plasma sources [1]. In these discharges, the wave produces the plasma and the plasma produced sustains the wave propagation. Depending on the type of the waves, the GWSDs show up in two modifications: surface-wave-sustained discharges as plasma sources without external magnetic field and Trivelpiece-Gould sustained discharges for plasma production in an external magnetic field. These discharges exist in the total gas-pressure range (p = 10^{-5} Torr ÷ 1 Atm) of the gas discharges and in a very wide range of variation of the wave frequency (f= 500 kHz ÷ 10 GHz). This flexibility makes the GWSDs very attractive for the gas-discharge applications [2].

In the GWSDs, the plasma column is extended far away from the wave launcher. The characteristics of the plasma (plasma density n, electron temperature T_e, etc.) and of the wave (wavenumber $k = \beta + i\alpha$, wave energy flux S, intensity of the wave electric field $|E|^2$) vary along the discharge length (z-direction) being self-consistently related to each other. This clear display of self-consistency makes the GWSDs a "pure" example for the definition of the gas discharges – as nonlinear systems which unify in a self-consistent manner plasmas and fields – and motivates the interest in their modelling [3].

2. Structure of the fluid-plasma models of the guided-wave-produced plasma sources

According to the nature of the GWSDs, the models of the discharges combine electrodynamics with gas-discharge physics.

The wave-energy balance – $d\overline{S}/dz = -\overline{Q}$ – is the first equation of the electrodynamical part of the models, with Joule heating $Q(r,z)$ and S integrated over the cross section of the waveguide structure (a plasma column in a glass tube with permittivity ε_g and internal and external radii R and R_1, surrounded by free space). This equation is usually used in its well-known form [4]:

$$\frac{d\bar{n}}{dz} = \frac{-2\alpha\bar{n}}{1 + \dfrac{\bar{n}}{\Theta}\dfrac{d\Theta}{d\bar{n}} - \dfrac{\bar{n}}{\alpha}\dfrac{d\alpha}{d\bar{n}}} \qquad (1)$$

where $\bar{n}$ is the averaged – over the plasma column cross section – plasma density, α is the space damping rate of the wave and $\Theta(z) = \overline{Q}(z)/\pi R^2 \bar{n}(z)$ is the power absorbed on average by an electron.

Equation (1) shows that the self-consistent description of the axial structure of the discharge requires to have the $(\bar{n}-\alpha)$- and $(\bar{n}-\Theta)$- relations known.

The $(\bar{n}-\alpha)$-relation comes out from the dispersion law of the wave

$$D(\omega, k = \beta + i\alpha, \varepsilon, R, R_1, \varepsilon_g) = 0 \qquad (2)$$

which is the second equation of the electrodynamical part of the discharge models. Here $\varepsilon(r,z)$ is the plasma permittivity.

The $(\bar{n}-\Theta)$-relation results from the gas-discharge part of the models. It is completed by the balance equations of production and losses of charged particles

$$\left(\frac{\delta n_{e,i}}{\delta t}\right)_{loss} = \left(\frac{\delta n_{e,i}}{\delta t}\right)_{gain}, \qquad (3)$$

specified for the given discharge considered, and by the electron energy balance

$$dP_\chi + dP_{coll} = Q \qquad (4)$$

in which, energy losses through thermal conductivity and collisions are taken into account.

Equation (3), describing the radial (r-) structure of the discharge, results into the condition of the discharge maintenance expressed by a $[T_e - n(r=0)]$-relation provided nonlinear processes are taken into account. With eq. (4) relating T_e to Θ, both (3) and (4) finally determines the $(\bar{n}-\Theta)$-relation. Since Θ is related to the maintenance field intensity, the $(\bar{n}-\Theta)$-relation expresses the basis of the description of the discharge as a nonlinear structure. Whereas the $(\bar{n}-\alpha)$-relation is a specific characteristic of the GWSDs, the $(\bar{n}-\Theta)$-relation is a basic concept of self-consistency of the high-frequency discharges, in general.

The numerical models [5-12] presented here of discharges in different gases (argon, helium, helium-argon gas mixtures and hydrogen) as well as of discharges in an external magnetic field, being extension and further development of ideas from the analytical modelling of surface-wave-sustained discharges [3], stresses the mechanisms of discharge

self-consistency and of the electron heating in the wave field.

3. Electron heating in the wave field

The mechanisms of the wave damping determine the mechanisms of the electron heating. In the numerical models presented here, the wave dispersion law (2) is for radially-inhomogeneous collisional plasmas, with radial profile of the plasma density and electron-neutral elastic collision frequency as obtained in the gas-discharge part of the models. Regimes of weak ($\nu < \omega$) and strong ($\nu \geq \omega$) collisions could be considered which permits covering the total range of the variation of the gas pressure of diffusion-controlled discharges in a combination with the total range of variation of the wave frequency. A display – along the discharge length – is shown of conditions of local heating with wave power deposition in the total plasma volume and of nonlocal heating with spacially-localized power deposition, including regions of resonance absorption of the waves.

4. Mechanisms of the discharge self-consistency

The nonlinear mechanisms relating n to Θ or, equivalently to the maintenance field intensity, ensures a self-consistent description of the discharge. It could be achieved if the condition for the discharge maintenance obtained from the charged-particle balance (3) relates the plasma density n to the electron temperature T_e.

In the models of discharges in atomic gases – argon, helium and helium-argon gas mixtures – the nonlinear processes of step ionization and recombination are the mechanisms, which ensure the self-consistency. The condition for the discharge maintenance obtained, e.g., in the models of argon discharges is:

$$\left(\frac{\mu}{R}\right)^2 D_{A\perp} + \rho_r n(r=0) = \nu_i + \frac{\rho_{si} n(r=0)}{1+\eta n(r=0)}. \quad (5)$$

Here $D_{A\perp}$ is the corresponding – without and with external magnetic field – ambipolar diffusion coefficient, μ is the parameter characterizing the radial plasma density inhomogeneity, ν_i is the frequency of direct ionization, ρ_{si} is the rate of step ionization with η being the coefficient of its saturation and ρ_r is the recombination coefficient.

Being an obvious generalization of the Schottky condition – $(\mu/R)^2 D_{A\perp} = \nu_i$ – in a sense that the total losses through diffusion and recombination are compensated by the total ionization (direct and step ionization), condition (5) relates the plasma density n to T_e and, respectively, to Θ, and ensures the self-consistency of the models. Regarding GWSDs, this means that the required interrelation between the axial profiles of $\bar{n}$ and Θ is achieved.

The models of gas discharges in helium and helium-argon gas-mixtures show that the ambipolar diffusion coefficient defined – after detailed analysis of the ion dynamics – as an effective one, is an additional factor of self-consistency.

The model of hydrogen discharges shows that the hydrogen atom yield in the discharge is the main factor which ensures the discharge self-consistency.

5. Axial self-consistent structure of the discharges

The final results from the models are for the self-consistent axial structures of the discharges composed out from the interrelated axial variation of $\bar{n}$, T_e, Θ, β and α. In discharges in helium-argon gas mixtures and in hydrogen discharges, the axial profiles of the concentration of the ion components also enter the discharge structure. Moreover, in hydrogen discharges, the axial variations of the concentration of the neutral gas species and of the gas temperature are important component of the structure of the discharge.

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